Europ. J. Agronomy 33 (2010) 103–116

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Adaptation of maize production to climate change in North China Plain: Quantify the relative contributions of adaptation options

Fulu Tao[a,*], Zhao Zhang[b]

[a] Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[b] State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China

ARTICLE INFO

Article history:
Received 9 September 2009
Received in revised form 30 March 2010
Accepted 9 April 2010

Keywords:
Adaptation
Agriculture
China
Climate change
Food security
Impact and vulnerability

ABSTRACT

Adaptation is a key factor that will shape the future severity of climate change impacts on food production. We need to evaluate the relative potential of adaptation strategies, and to develop effective adaptation strategies to cope with climate risk. Here, we apply a super-ensemble-based probabilistic projection system (SuperEPPS) to project maize productivity and evapotranspiration (ET) over growing period during 2050s in the North China Plain, and to examine the relative contributions of adaptation options. Based on a large number of simulation outputs from the super-ensemble-based projection, our results show that without adaptation maize yield could decrease averagely by 13.2–19.1%, and ET during growing period could decrease by 15.6–21.8% during 2050s, relative to 1961–1990. In comparison with the experiment without adaptation, using high-temperature sensitive varieties, maize yield could averagely increase by 1.0–6.0%, 9.9–15.2%, and 4.1–5.6%, by adopting adaptation options of early planting, fixing variety growing duration, and late planting, respectively. ET could averagely increase by 1.9–4.4%, 1.9–3.7%, and −2.9% to −0.7%, respectively. In contrast, using high-temperature tolerant varieties, maize yield could averagely increase by −2.4% to −1.4%, 34.7–45.6%, and 5.7–6.1%, respectively. ET could averagely increase by 0.7–0.9%, 9.4–11.6%, and −0.4% to 0.2%, respectively. The spatial patterns show that the relative contributions of adaptation options can be geographically quite different, depending on the climate and variety properties. The biggest benefits will result from the development of new crop varieties that are high-temperature tolerant and have high thermal requirements.

1. Introduction

The ongoing climate change is projected to affect dramatically the development, water cycle and productivity of the staple crops in broad regions of the world although many uncertainties remain (e.g., Parry et al., 2004; IPCC, 2007). Climate change can impact the growth and development of crop in a number of ways. Changes in temporal and spatial pattern of precipitation directly impact crop water cycle and consequently water stress on crop development (Tao et al., 2003a,b). Temperature, particularly change in maximum and minimum temperature, is a key determinant of evaporative and transpirative demand (e.g., Priestley and Taylor, 1972; Roderick and Farquhar, 2002). Temperature-induced increases in evapotranspiration could aggravate drought stress (Tao et al., 2003a,b). Sustained temperature increases over the season will change the duration (from sowing to maturity) of the crop (e.g., Roberts and Summerfield, 1987), which is one of important causes for yield reduction under climate change (e.g., IPCC, 2007; Tao et al., 2008a). Short episodes of high temperature at critical stages of crop development can cause sterility and consequently yield reduction independently of any substantial changes in mean temperature (e.g., Wheeler et al., 2000; McKeown et al., 2005).

The long-term challenge of avoiding a perpetual food crisis under conditions of global warming is serious. Adaptation is a key factor that will shape the future severity of climate change impacts on food production (IPCC, 2007; Lobell et al., 2008), and has recently received increasing attention. Adaptation decisions occur on a range of temporal and spatial scales, from the crop management choices of smallholder agriculturalists, to the policy decisions made by governments and regional authorities. As a result, adaptation options can be developed using climate forecasts across a range of timescales, from days to decades (Adger et al., 2005; Challinor, 2009). At seasonal or yearly timescales, a food security warning system, usually consisting of seasonal weather forecasting information and crop forecasting system, makes better use of seasonal climate forecasts to reduce production risks (e.g., Meza and Wilks, 2003; Hansen et al., 2006), providing a means of adapting to climate variability/change. At multi-decadal timescales, the general approaches to adaptation took a ‘top-down’ perspective, moving from global climate model scenarios to sector impact stud-

* Corresponding author.
E-mail addresses: taofl@igsnrr.ac.cn (F. Tao), zhangzhao@bnu.edu.cn (Z. Zhang).

1161-0301/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.eja.2010.04.002

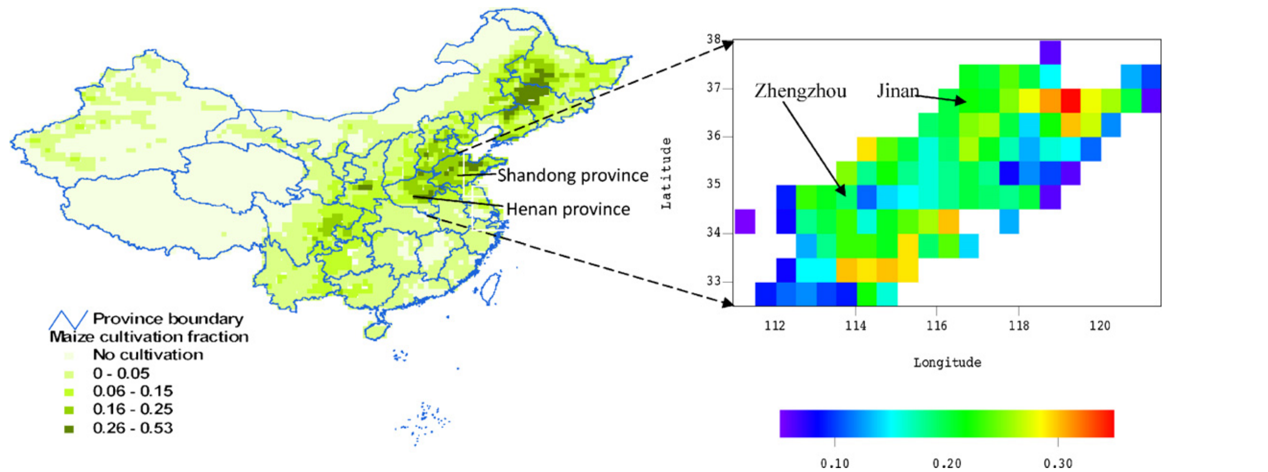

Fig. 1. Maize cultivation fraction (the ratio between maize cultivation area and total area in a grid) in China at 0.5 × 0.5 grid resolution, the provinces and the grids investigated in this study.

ies and then to assessments of adaptation options (e.g., IPCC, 2007; Challinor, 2009). The IPCC forth assessment report (IPCC, 2007) suggested several adaptation strategies to deal with projected climatic changes which include, changing varieties; more efficient water use; altering the timing or location of cropping activities; and improving the effectiveness of pest, disease and weed management practices, etc.

The North China Plain (NCP) is one of major agricultural production areas in China, with mean precipitation of 500–600 mm/year, and annual crop actual evapotranspiration (ET) of 800–900 mm. Shortage of water resources has become a key concern of sustainable crop production. In the last several decades, there has been an increasing trend in agricultural water demands, soil drying and soil-moisture variability on the NCP (Tao et al., 2003a). Due to the shortage of surface water, especially in the north part of the NCP, groundwater becomes an important source of irrigation water. Groundwater level is persistently declining due to overpumping, which creates a cone of depression at some areas (Jia and Liu, 2002). The NCP could be one of most vulnerable regions to climate change due to increasing temperature and water-related challenges (Tao et al., 2003a,b; Xiong et al., 2007; Mo et al., 2009). Maize is most vulnerable to climate variability and change among the staple crops in the NCP (Tao et al., 2004, 2008b). For example, in the last several decades, maize yields were significantly correlated to seasonal precipitation in Shandong and Hebei provinces (Tao et al., 2008b); maize yields in Henan province decreased significantly by 16% during the El Niño phase, in comparison to the neutral phase (Tao et al., 2004).

We need to evaluate the relative potential of adaptation strategies, and to develop effective adaptation strategies to cope with climate risk. Furthermore, a full assessment of the climate change impacts on agricultural production should take comprehensively into account available adaptation strategies (Reidsma et al., 2010), and account for the uncertainties from many physical, biological, and social-economic processes (Tubiello et al., 2007; Tao et al., 2009a). Modelling studies can contribute to policy by providing the science to underpin strategic decisions. In the present study, we apply a super-ensemble-based probabilistic projection system developed by Tao et al. (2009a,b) to examine the relative contributions of adaptation options in projecting maize productivity and water use during 2050s (2041–2070) in Henan and Shandong province in the NCP (Fig. 1). Addressing the impacts and adaptation options in the 'climate risk hot spot' can become an important example in seeking effective adaptation strategies for other regions. The general methodology and framework presented here can also be applied for other regions and crops.

2. Materials and methods

2.1. The super-ensemble-based probabilistic projection system (SuperEPPS)

Estimates of climate change impacts are plague with uncertainties from many physical, biological, and social-economic processes. Tao et al. (2009a,b) developed a new SuperEPPS to account for the uncertainties not only from CO_2 emission scenarios and climate change scenarios but also from biophysical processes, and to assess the impacts of climate change on crop productivity and water use in a probabilistic framework. The system used 10 climate scenarios consisting of the combinations of five GCMs and two emission scenarios, the corresponding atmospheric CO_2 concentration range, and 60 sets of optimal crop model parameters optimized with the Bayesian probability inversion and a Markov chain Monte Carlo (MCMC) technique, to drive the well-validated process-based general crop model, MCWLA (Tao et al., 2009b). The use of multi-climate scenarios and sets of crop model parameters is to represent uncertainties from many physical, biological and social-economic processes. The SuperEPPS has been demonstrated in addressing the impacts of climate variability (change) on probabilistic changes of maize production in the NCP (Tao et al., 2009b). Yield hindcasts by the SuperEPPS can significantly capture the interannual variability in maize yields in all the four investigated provinces (including Henan and Shandong provinces in this study) from 1985 to 2002. Agreement between observed and modelled yields is variable, with correlation coefficients ranging from 0.03 to 0.88 ($p < 0.01$) at the model grid scale and from 0.45 to 0.82 ($p < 0.01$) at the province scale.

As the core of the SuperEPPS, the crop model MCWLA is designed to account for the key impact mechanisms of climate variability (change) and be accurate over a large area. MCWLA simulates crop growth and development in a daily time-step. Growing degree-days provide the driving force for the processes of canopy development, flowering, and maturity. The effective temperature for crop development and thermal time accumulation is defined using cardinal temperatures, i.e. the base (Tb), optimum (To), and maximum temperature (Tm). Crop growth and development will be inhibited if daily temperature is below Tb or above To. Therefore, the impacts of temperature on crop phenology and growing period, as well as the impacts of extreme temperature on crop growth and development, such as development of daily leaf area index (LAI) and root depth, are taken into account. MCWLA simulates the impacts of extreme temperature stress on daily photosynthesis using a temperature inhibition function limiting photosynthesis at low and high temperatures (Larcher, 1983). The impacts of drought and flooding are simulated through soil-moisture stress on daily LAI development and transpiration, subsequently on root development, photosynthesis, canopy conductance, and yield. ET is calculated as the minimum of a crop- and soil-limited supply function and the atmospheric demand. MCWLA includes the process-based representation of the coupled CO_2 and H_2O exchanges by photosynthesis–stomatal conductance coupling mechanisms. It accounts mechanically for the impacts of climate variables and elevated [CO_2] on canopy net photosynthesis, stomatal conductance and transpiration rate. Its simulations on the responses of LAI, canopy conductance, canopy transpiration rate and yield to elevated CO_2 concentration, in both drought and wet years, agree well with the controlled-environment experiments (Tao et al., 2009b).

2.2. Data

The MCWLA model requires daily weather inputs for mean temperature, precipitation, vapour pressure, and fractional sunshine hours. Daily weather for maximum and minimum temperature, precipitation and solar radiation is an alternative set of inputs. In this study, the MCWLA is run at each $0.5^\circ \times 0.5^\circ$ grid with maize cultivation fraction (the ratio between maize cultivation area and total area in a grid) ≥ 0.05 across two major production provinces, i.e. Henan and Shandong province (Fig. 1). There are totally 47 grids in Henan province and 54 grids in Shandong province. Monthly data on mean temperature, precipitation, vapour pressure, wet days and fractional sunshine hours for the $0.5^\circ \times 0.5^\circ$ resolution grids from 1901 to 2002 are obtained from the Climatic Research Unit, University of East Anglia, U.K. (Mitchell and Jones, 2005).

For the future climate change scenarios, the 10 scenarios for monthly fields of mean temperature, precipitation, vapour pressure and fractional sunshine hours on a 0.5° grid from 2001 to 2100 are also taken from the Climatic Research Unit, University of East Anglia (Mitchell et al., 2004). The scenarios comprise all 10 combinations of two emission scenarios (A1FI, B1) and five GCMs (HadCM3, PCM, CGCM2, CSIRO2 and ECHAM4), using GCMs outputs from the IPCC Data Distribution Centre. The detailed information on the GCMs can be found at http://www.ipcc-data.org/. The complete method of dataset construction was described in Mitchell et al. (2004). These GCMs are among the state-of-the-art GCMs for impacts study. The low emission scenario (B1) and fossil intensive emission scenario (A1FI) are chosen to cover the wide ranges of emission scenarios and climate change scenarios in future. Ten different futures are used to represent the uncertainty in climate impacts arising from two distinct uncertainty sources: uncertainty in the future emissions of greenhouse gases and uncertainty in climate modelling. Each of the 10 permutations is treated as equally likely (Mitchell et al., 2004). In the development of the dataset, to remove the effects of multi-decadal variability, the variability observed in the 20th century was superimposed on the mean changes projected for the 21st century (Mitchell et al., 2004). Thus, the climate scenarios of the 21st century replicate the observed month-to-month, interannual, and multi-decadal climate variability of the detrended 20th century climate data. One consequence of this approach is that possible future changes in multi-decadal or interannual variability are not included in these scenarios.

The monthly means of temperature, vapour pressure and fractional sunshine hours were interpolated to daily values using spline interpolation (Press et al., 1992). As in the previous study (Tao et al., 2009b), monthly precipitation under both baseline climate condition and future climate scenarios is interpolated to daily values using a weather generator, with monthly total precipitation and wet days as inputs, after Gerten et al. (2004). The monthly wet days in the 21st century are assumed to replicate the observed values in the 20th century, because the variable is not available in the future climate change scenarios. The mean CO_2 concentration would range from 498.5 ppmv under B1 scenario to 602.5 ppmv under A1FI scenario during 2050s (IPCC, 2001).

As Tao et al. (2009a,b), soil texture and hydrological properties data are based on the FAO soil dataset (Zobler, 1986; FAO, 1991). Soil parameters include the soil-texture-dependent percolation rate (mm d^{-1}) at field capacity and available volumetric water holding capacity (i.e., the water holding capacity at field capacity minus water holding capacity at the wilting point, expressed as a fraction of soil layer depth).

2.3. Modelling experiments

We use two varieties with contrasting thermal properties to investigate the relative contributions of agricultural adaptation options in reducing losses from projected climate change by four modelling experiments.

The cardinal temperatures for maize growth and development, i.e. Tb, To, and Tm is, respectively, 9.1, 28.7, and 32.5 °C for variety I, and 8.9, 30.2, and 35.3 °C for variety II. The thermal time requirement from planting to maturity is 1666.1 degree-days and 1710.9 degree-days for varieties I and II, respectively. Although the two varieties share the same 60 sets of parameters related to light use, water use, and yield formation processes as Tao et al. (2009b). The two sets of variety thermal parameters were selected from the optimal 60 sets of parameters of MCWLA in simulating the interannual variability of maize phenology and productivity in the NCP. The optimal 60 sets of parameters were derived by applying the Bayesian probability inversion and a Markov chain Monte Carlo (MCMC) technique to the MCWLA based on the maize phenology and yield records from 1995 to 2002 in the NCP (Tao et al., 2009a). According to Tao et al. (2009a), the 97.5% high-probability intervals for Tb, To, Tm and thermal time requirement from planting to maturity in the NCP are from 7.9 to 10.0 °C, 27.7 to 30.9 °C, 31.1 to 35.9 °C, and 1590.4 to 1788.7 degree-days, respectively.

Four modelling experiments are designed to examine the relative contribution of agricultural adaptation options. Experiment I allows crop planting on the first day when soil water meets a requirement in a 2-week window centered on current common planting date, otherwise the final day of the window. This setting is the usual way in current impact assessment studies, representing no adaptation, business as usual, or unchanged in future. Experiment II is set as Experiment I, but the 2-week window is shift 10 days in advance, representing early planting for about 10 days. Experiment III is set as Experiment I, but crop growing duration (days from planting to maturity) under future climate condition is set to be same as that under baseline climate (crop growing duration is not changed under climate change), suggesting use of a variety with long growing duration or with high thermal requirement. Experiment IV is set as Experiment I, but the 2-week window is postponed for 10 days, representing late planting.

2.4. Analysis

For each of the four experiments, across all the maize cultivation grids in each province, we derive the probability density functions (PDFs) of maize yield and ET changes during 2050s, relative to 1961–1990, based on a large number of simulation outputs from the super-ensemble-based projection. We compare the changes in PDFs and statistics, derived from the outputs of the four modelling experiments, to evaluate the relative contributions of the adaptation strategies. To further investigate the spatial patterns, we also plot the spatial patterns of mean yield and ET during the period of 1961–1990, and their changes during 2050s using different adaptation options, on a resolution of $0.5^\circ \times 0.5^\circ$ grids across the study region.

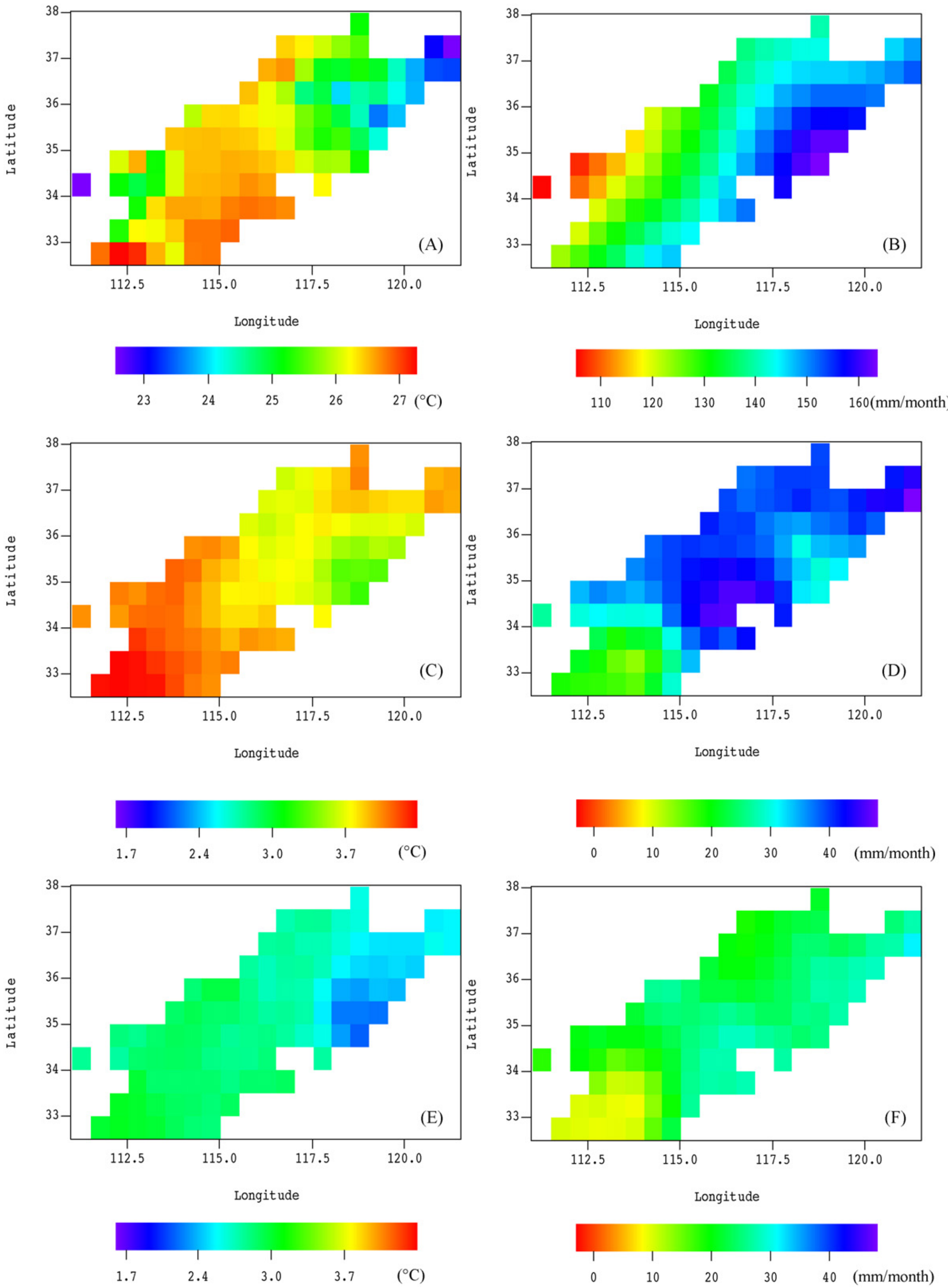

Fig. 2. Spatial patterns of mean temperature (A) and monthly precipitation (B) in summer (June–July–August) during 1961–1990, and the projected changes in mean temperature (C, E, G, I) and monthly precipitation (D, F, H, J) during 2050s, based on HadCM3 GCM and A1FI emission scenario (C, D), HadCM3 GCM and B1 emission scenario (E, F), CGCM2 GCM and A1FI emission scenario (G, H), and CGCM2 GCM and B1 emission scenario (I, J), respectively.

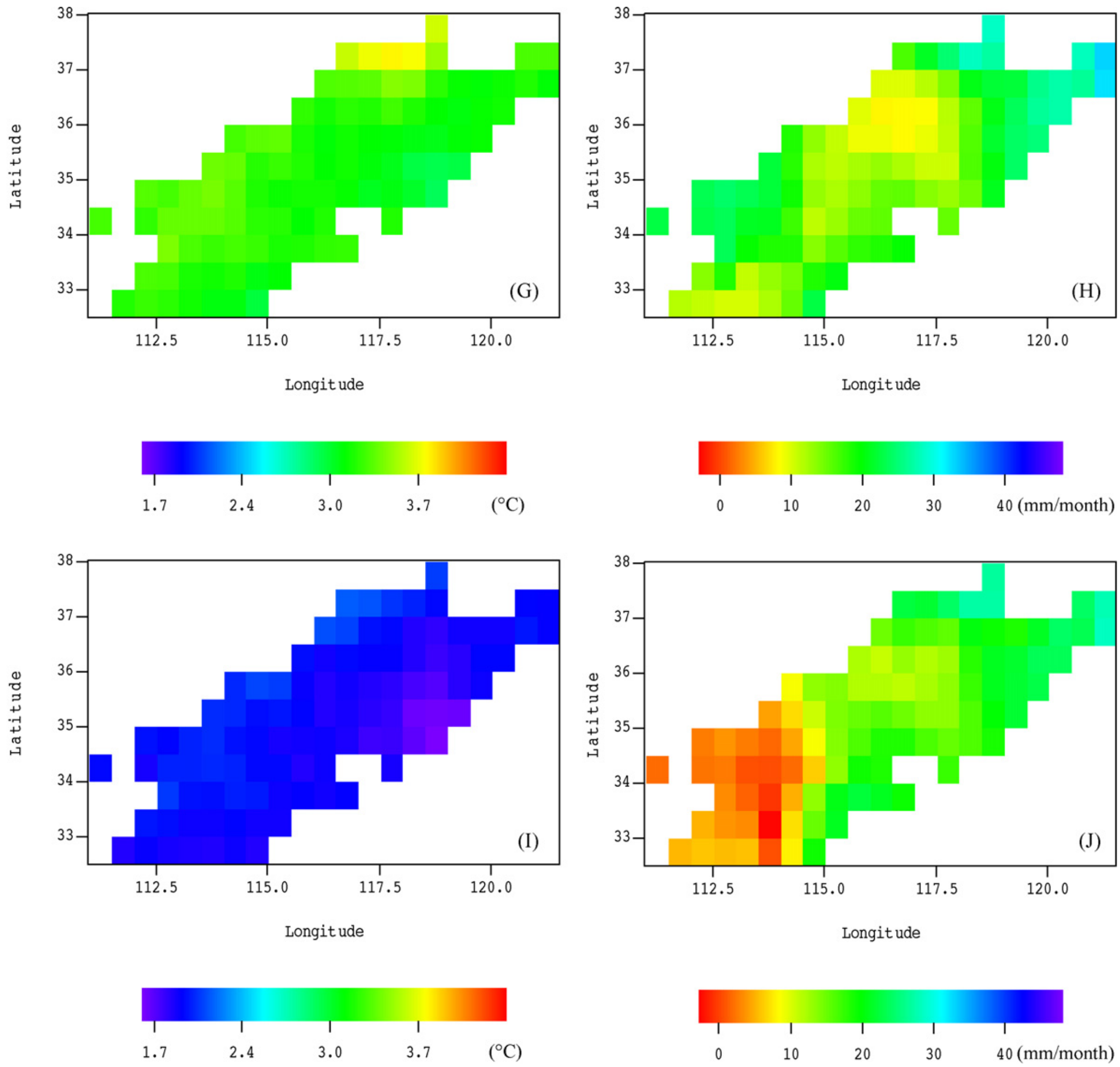

Fig. 2. (*Continued*.)

3. Results

3.1. Climate change scenarios of seasonal temperature and precipitation

During the period of 1961–1990, mean temperature ranged generally from 22 to 27 °C in summer (June–July–August), with the highest located in the south and southeast parts of Henan province (Fig. 2A); mean monthly precipitation ranged generally from 110 to 160 mm, with the least located in the west part of Henan province (Fig. 2B). During the period of 2041–2070, both temperature and precipitation is projected to increase generally across the region. As examples, from the 10 climate change scenarios used in the study, we illustrated the spatial patterns of 4 scenarios as follows. Based on HadCM3 GCM and A1FI emission scenario, during the period of 2041–2070, mean temperature could increase generally from 3.3 to 4.4 °C in summer, relative to 1961–1990, with the highest increase located in the southwest part of Henan province (Fig. 2C). Mean monthly precipitation could increase generally from 13 to 48 mm, with the least increase also located in the southwest part of Henan province. Using HadCM3 GCM and B1 emission scenario, mean temperature could increase generally from 2.2 to 3.1 °C in summer (Fig. 2E), and mean monthly precipitation could increase generally from 8.8 to 31.5 mm (Fig. 2F). Based on CGCM2 GCM and A1FI emission scenario, mean temperature could increase generally from 2.9 to 3.8 °C in summer, relative to 1961–1990, with the highest increase located in the north part of Shandong province (Fig. 2G). Mean monthly precipitation could increase generally from 7.9 to 32.8 mm, with the least increase located in the west part of Shandong province (Fig. 2H). Using CGCM2 GCM and B1 emission scenario, mean temperature could increase generally from 1.6 to 2.4 °C in summer (Fig. 2I), and mean monthly precipitation could increase generally from −3.0 to 28.2 mm, with the least located in the west part of Henan province (Fig. 2J).

3.2. Probabilistic changes in maize yield and ET using different adaptation strategies

Across the maize cultivation grids in Henan province, based on the 60 sets of parameters × 30 years × 10 scenarios × 47 crop grids = 846,000 simulations using variety I(II), the resulting probability distributions indicate expected yield changes of −13.2% (−15.4%), −7.2% (−16.8%), −3.3% (+30.2%), and −9.1% (−9.7%) during 2050s by Experiments I, II, III, and IV, in percent of 1961–1990 yields, respectively (Fig. 3A and C, Table 1). By Experiments III and IV, the peak of PDF for yield change shifts more to the positive side, and both the negative and positive tails become more extended

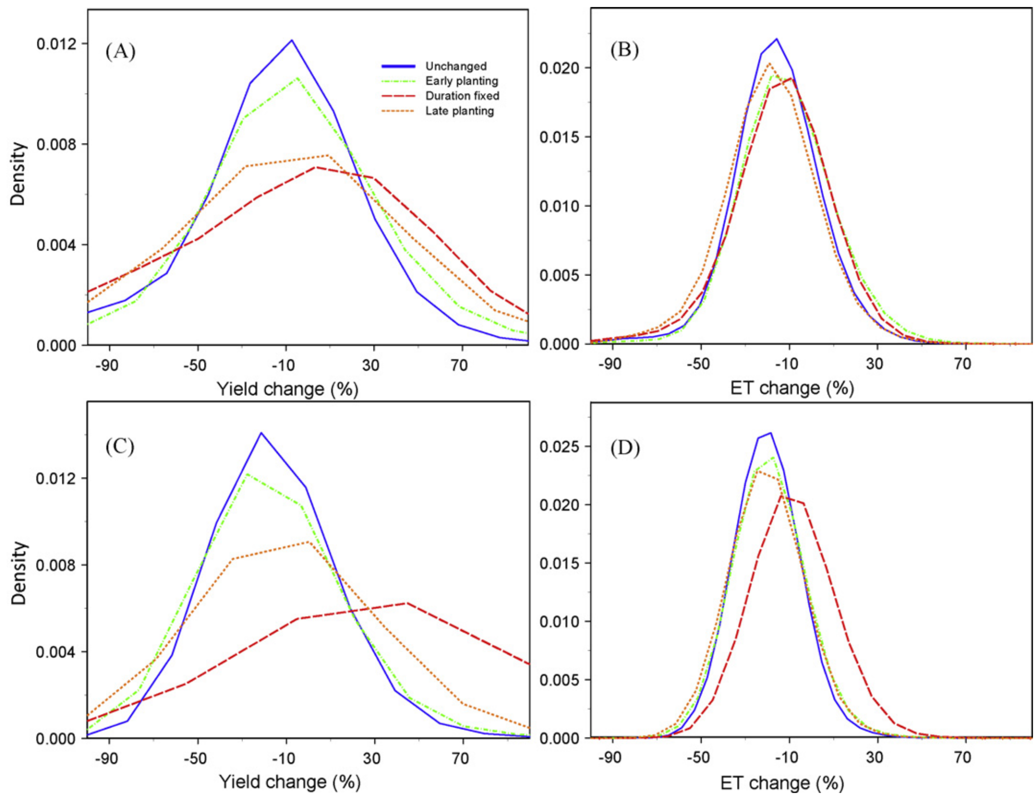

Fig. 3. Probability density functions of projected changes in maize yield (A, C) and ET (B, D) during 2050s, from Experiment I (unchanged), Experiment II (early planting), Experiment III(duration fixed), and Experiment IV (late planting), relative to 1961–1990, across the maize cultivation grids in Henan province using crop variety I (A, B) and II (C, D).

and stronger (Fig. 3A). As for ET, using variety I(II), the resulting probability distributions indicate expected ET changes of −15.6% (−20.0%), −11.2% (−19.1%), −13.7% (−8.4%), and −18.5% (−20.4%) during 2050s by Experiments I, II, III, and IV, relative to 1961–1990, respectively (Fig. 3B and D, Table 1). The PDFs of ET change do not change notably among the four experiments using variety I (Fig. 3B); in contrast, the PDF of ET change by Experiment III and using variety II shifts more to the positive side (Fig. 3D).

Across the maize cultivation grids in Shandong province, based on the 60 sets of parameters × 30 years × 10 scenarios × 54 crop grids = 972,000 simulations using variety I(II), the resulting probability distributions indicate expected yield changes of −14.7% (−19.1%), −13.7% (−21.5%), 0.45% (+15.6%), and −9.1% (−13.0%) during 2050s by Experiments I, II, III, and IV, in percent of 1961–1990 yields, respectively (Fig. 4A and C, Table 1). By the Experiment III, the peak of PDF for yield change shifts more to the positive side, and the positive tail becomes more extended and stronger, using both variety I and II (Fig. 3A and C). As for ET, using variety I (II), the resulting probability distributions indicate expected ET changes of −17.8% (−21.8%), −15.9% (−21.1%), −14.1% (−12.4%), and −18.5% (−21.6%) during 2050s by Experiments I, II, III, and IV, relative to 1961–1990, respectively (Fig. 4B and D, Table 1). The PDF of ET change by Experiment III shifts more to the positive side, using both varieties I and II (Fig. 3B and D).

3.3. Spatial patterns of maize yield and ET changes using different adaptation strategies

Using variety I, based on the 60 sets of parameters × 30 years × 10 scenarios = 18,000 simulations for each grid, maize yield was generally less than 5000 kg/ha during the period of 1961–1990 across the two provinces (Fig. 5A); ET during growing period ranged generally from 150 to 170 mm (Fig. 5B). Experiment I suggests that maize yield could generally decrease by 10–40% during 2050s without adaptation (Fig. 5C). Particularly, it could decrease notably in the south part of Henan province, and the north parts of Henan and Shandong provinces, where temperature would increase most and precipitation would increase least (Fig. 2). ET during growing

Table 1
Mean and 95% probability intervals (in parenthesis) of estimated change in maize yield and ET over growing period during 2050s by different experiments in percent of 1961–1990 level.

Province	Variety	Exp. I		Exp. II		Exp. III		Exp. IV	
		Yield (%)	ET (%)	Yield (%)	ET (%)	Yield (%)	ET (%)	Yield (%)	ET (%)
Henan	Variety I	−13.2 (−84.9, 36.7)	−15.6 (−43.5, 14.6)	−7.2 (−61.6, 50.1)	−11.2 (−38.0, 21.1)	−3.3 (−100.0, 69.0)	−13.7 (−47.2, 16.6)	−9.1 (−86.0, 44.2),	−18.5 (−49.3, 11.5)
	Variety II	−15.4 (−43.8, 22.3)	−20.0 (−42.7, 3.5)	−16.8 (−45.8, 24.3)	−19.1 (−41.8, 5.0)	30.2 (−25.5, 88.0)	−8.4 (−33.5, 18.6)	−9.7 (−41.1, 33.4)	−20.4 (−43.6, 3.4)
Shandong	Variety I	−14.7 (−47.0, 24.6)	−17.8 (−41.3, 8.0)	−13.7 (−43.9, 30.2)	−15.9 (−39.7, 11.6)	0.5 (−66.0, 59.8)	−14.1 (−39.5, 12.5)	−9.1 (−45.0, 34.2)	−18.5 (−42.1, 6.9)
	Variety II	−19.1 (−44.8, 14.9)	−21.8 (−43.9, 0.43)	−21.5 (−46.2, 12.2)	−21.1 (−42.9, 1.3)	15.6 (−32.0, 70.0)	−12.4 (−36.2, 13.5)	−13.0 (−42.3, 27.1)	−21.6 (−44.0, 0.9)

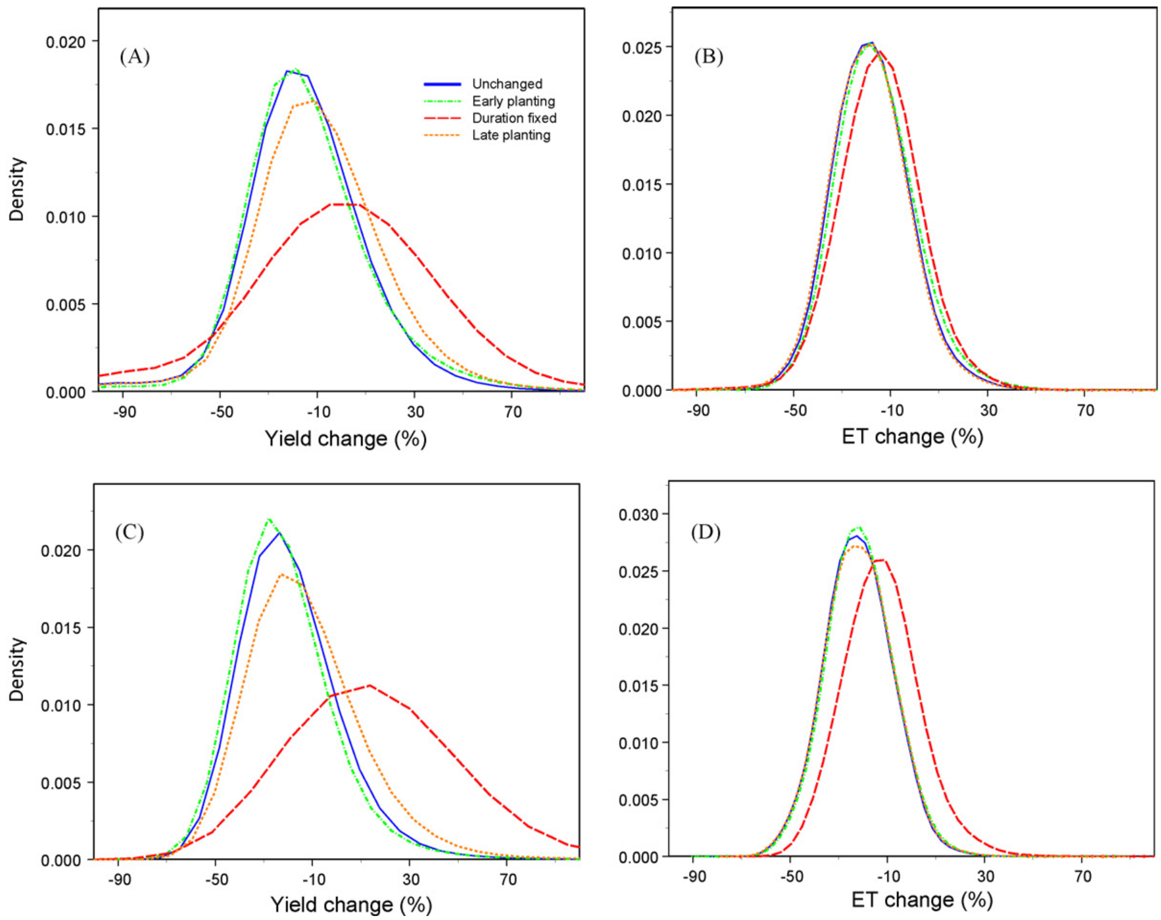

Fig. 4. Probability density functions of projected changes in maize yield (A, C) and ET (B, D) during 2050s, from Experiment I (unchanged), Experiment II (early planting), Experiment III (duration fixed), and Experiment IV (late planting), relative to 1961–1990, across the maize cultivation grids in Shandong province using crop variety I (A, B) and II (C, D).

period could decrease generally by 15–30% (Fig. 5D). Experiment II suggests that early planting could reduce yield loss due to climate change by about 10% in the south and southeast part of Henan province (Fig. 5E), and ET during growing period could decrease generally by 5–25% (Fig. 5F). Experiment III, by fixing crop growing duration, suggests that maize yield could increase notably in the east part of Shandong province, where temperature would increase least and precipitation would increase most (Fig. 2); however decrease more in most part of Henan province (Fig. 5G). ET during growing period could decrease generally from 10 to 30% (Fig. 5H). Experiment IV shows that late planting could increase yield loss due to climate change by about 10% in most part of Henan province (Fig. 5I); and ET during growing period could decrease generally by 15–30% (Fig. 5J). The standard deviation of projected yield changes is generally smaller in the east part of Shandong province with relatively higher yield than those in the south part of Henan province with relatively lower yield (not shown).

Using variety II, based on the 60 sets of parameters × 30 years × 10 scenarios = 18,000 simulations for each grid, maize yield and ET during growing period was generally higher in comparison with variety I, during the period of 1961–1990 (Fig. 6A and B). Experiment I suggests that maize yield could generally decrease by 10–30% during 2050s across the two provinces without adaptation (Fig. 6C). Particularly, yield could generally decrease by about 30% in the east part of Shandong province; in contrast, decrease less in the south part of Henan province. ET during growing period could generally decrease by 15–30% (Fig. 6D). Experiment II suggests that early planting could reduce yield loss due to climate change in the south part of Henan province, however increase yield loss slightly in the east part of Shandong province (Fig. 6E). ET during growing period could generally decrease by 10–30%. Experiment III, by fixing crop growing duration, suggests that maize yield could increase notably by up to 50% at the most area of the two provinces (Fig. 6G); and ET during growing period could generally decrease by 5–20%. Experiment IV suggests that late planting could generally reduce yield loss due to climate change by about 10% at the most area of the two provinces (Fig. 6I); and ET during growing period could generally decrease from 15 to 30%.

3.4. Mechanisms underlying the adaptation strategies

The processes and mechanisms of crop model MCWLA in simulating high temperature and drought stress have been addressed in Section 2.1. To gain insight into the mechanisms underlying the adaptation options in this study, as an example, we compare the climate, crop development and productivity in 1990 and 2070 in the grid of Zhengzhou (centering on latitude 34.75, longitude 113.75) in Henan province and the grid of Jinan (centering on latitude 36.75, longitude 116.75) in Shandong province, respectively (Fig. 1). In the grid of Zhengzhou, daily temperature was near to T_o for the variety I and below T_o for the variety II during growing period in 1990. Based on HadCM3 GCM and A1FI emission scenario, mean temperature and precipitation in summer could increase by 4.8 °C and 22.2 mm/month, respectively, relative to 1990 (Fig. 7A). As a result, daily temperature could be above T_o and even T_m for the variety I, and T_o for the variety II on some days during growing period, consequently the development and productivity of crop could be inhibited without adaptation. For the variety I, early planting and fixing crop growing duration could not prevent crop development and productivity from high-temperature stress thoroughly, as indicated by the daily development of LAI (Fig. 7B) and canopy transpiration (Fig. 7D). Late planting could better prevent crop development and productivity from high-temperature stress at key development stages, although crop transpiration and photosynthesis rate could reduce notably and crop thermal requirement could not be met during growing season (from June to beginning of October). Finally early planting could reduce yield loss due to climate warming (Fig. 7F). For the variety II, the impacts of high-temperature stress could be much less, all the three adaptation options could reduce yield loss due to climate warming, particularly fixing crop growing duration and early planting could be more effective (Fig. 7C, E, and G).

In the grid of Jinan, daily temperature was near to *To* for the variety I and below *To* for the variety II during growing period in 1990. Based on HadCM3 GCM and A1FI emission scenario, mean temperature in summer could increase by 3.8 °C and precipitation could decrease by 30.9 mm/month, respectively, relative to 1990 (Fig. 8A). As a result, daily temperature could be above *To* for both varieties on

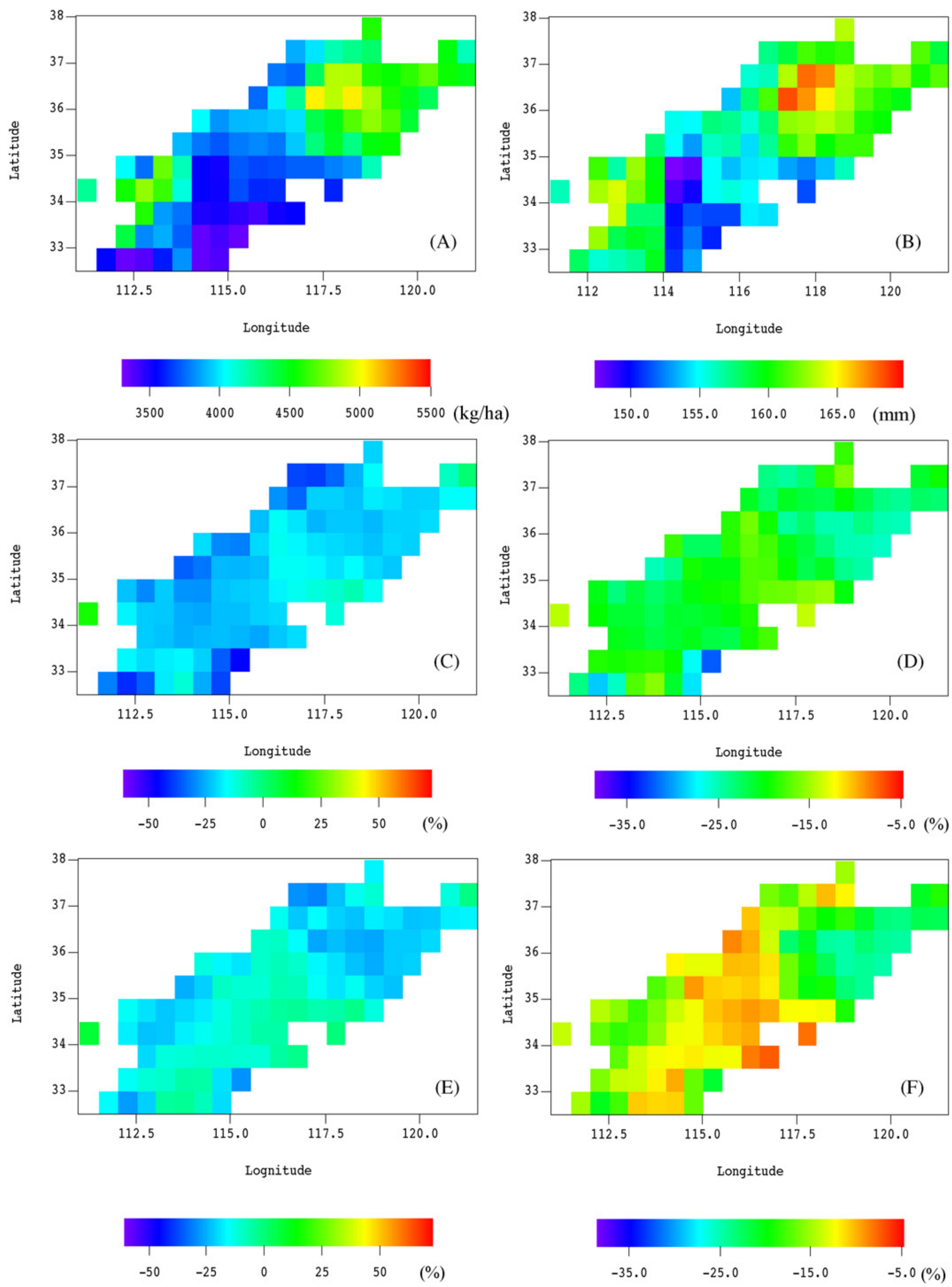

Fig. 5. Spatial patterns of simulated maize yield (A) and ET (B) during 1961–1990, and the projected changes in yield (C, E, G, I) and ET (D, F, H, J) during 2050s from the Experiments I (C, D), II (E, F), III (G, H), IV (I, J), respectively, using the variety I.

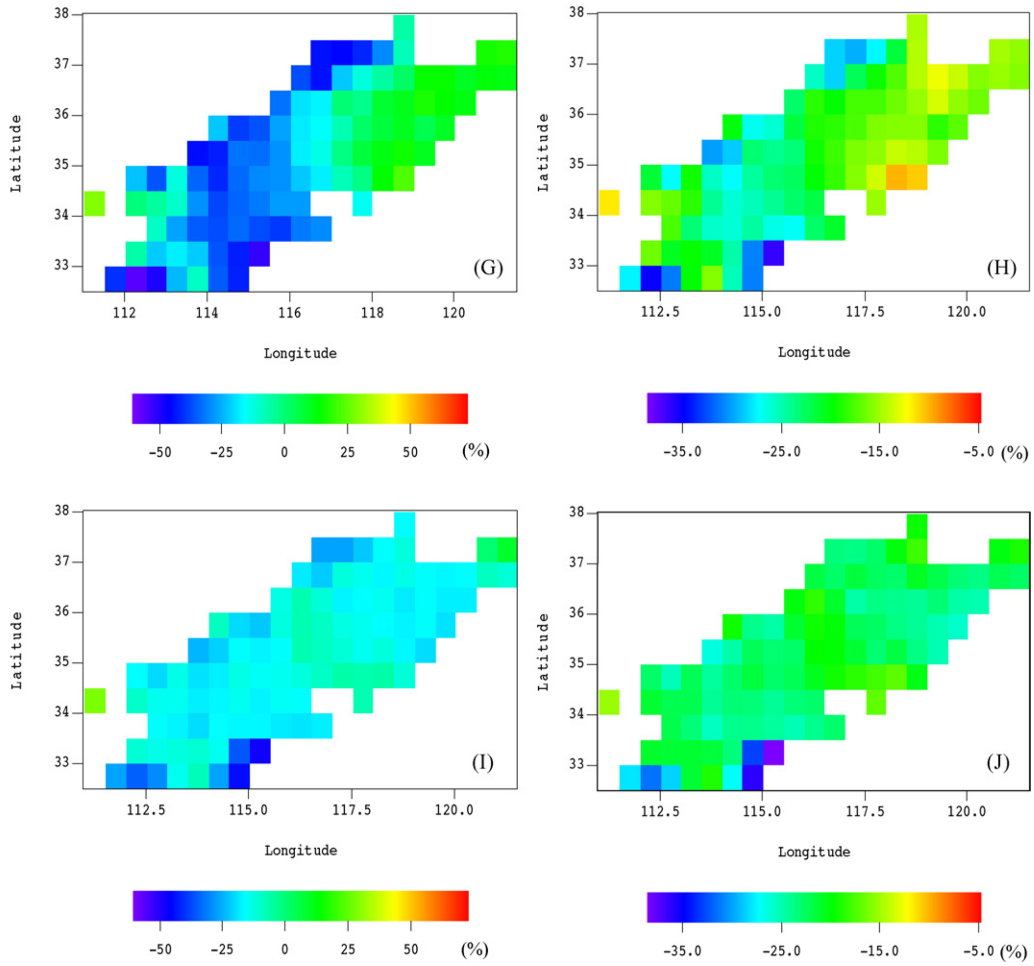

Fig. 5. (*Continued*.)

some days during growing period, consequently the development and productivity of crop could be inhibited without adaptation to some extent. For the variety I, early planting and fixing crop growing duration could not prevent crop development and productivity from high-temperature stress thoroughly, as indicated by the daily development of LAI (Fig. 8B) and canopy transpiration (Fig. 8D). Late planting could better prevent crop development and productivity from high-temperature stress at key development stages, although crop transpiration and photosynthesis rate could reduce notably and crop thermal requirement could not be met during growing season (from June to beginning of October). Finally early planting could reduce yield loss due to climate warming (Fig. 8F). For the variety II, the impacts of high-temperature stress could be much less. Crop growth duration could reduce more by early planting, and crop transpiration and photosynthesis rate could reduce notably by late planting. Adopting the varieties that are high-temperature tolerant and have high thermal requirements could be a potential adaptation option, which could make full use of increased heat resources due to climate change (Fig. 8C, E and G).

4. Discussion

4.1. Adaptation of maize production to climate change in the NCP

Based on a large number of simulation outputs from the super-ensemble-based projection, the results show that maize yield and ET during growing period could have different changes by using different varieties or/and adopting the adaptation strategies of early planting, fixing crop growing duration, or late planting, in comparison with the experiment without adaptation. Our findings suggest that for some high-temperature sensitive varieties such as variety I, early planting should be a generally effective adaptation option to reduce yield loss from climate change averagely by about 6.0%; in contrast, for some high-temperature tolerant varieties such as variety II, late planting could be a generally effective adaptation option to reduce yield loss averagely by about 5.7%. Although the relatively inexpensive adaptation options may moderate negative impacts to some extent, the biggest benefits will result from the development of new crop varieties that are high-temperature tolerant and have high thermal requirements. It seems that such kinds of new crop varieties can be obtained in future (e.g., Young et al., 2001; Hannah, 2007). The spatial pattern shows that the relative contributions of adaptation options can be quite different geographically, depending on the climate and variety properties, suggesting the optimal adaptation options should be region and variety specific.

Due to rising CO_2 concentration, ET during maize growing period is projected to reduce by up to 30%, relative to 1961–1990. Even using the new crop varieties that are high-temperature tolerant and have high thermal requirements, as illustrated by the Experiment III using variety II in this study, yield could increase notably (Fig. 6G), and ET could reduce averagely by up to 15% (Fig. 6H). Furthermore, precipitation is projected to increase generally in the region. These findings suggest that water stress on maize production in the NCP could be eased to some extent in future.

The study focuses on the adaptation strategies of the most vulnerable rainfed crop production at multi-decadal timescales with assumption of no nutrition stress. Besides the adaptation options mentioned above, other adaptation strategies can be effective for agricultural systems to adapt to climate change, such as changing cropping system (Meza et al., 2008), switching from highly impacted to less impacted crop (Lobell et al., 2008), improving pest and disease forecast and control, and improving inputs such as water supply and irrigation system, tillage methods, grain drying, fertilization application and other field operations (Reilly and Schimmelpfenning, 1999). At seasonal or yearly timescales, early warning and risk management systems are obviously efficient to reduce disasters, and can facilitate adaptation to climate variability and change (Meza and Wilks, 2003; Hansen et al., 2006).

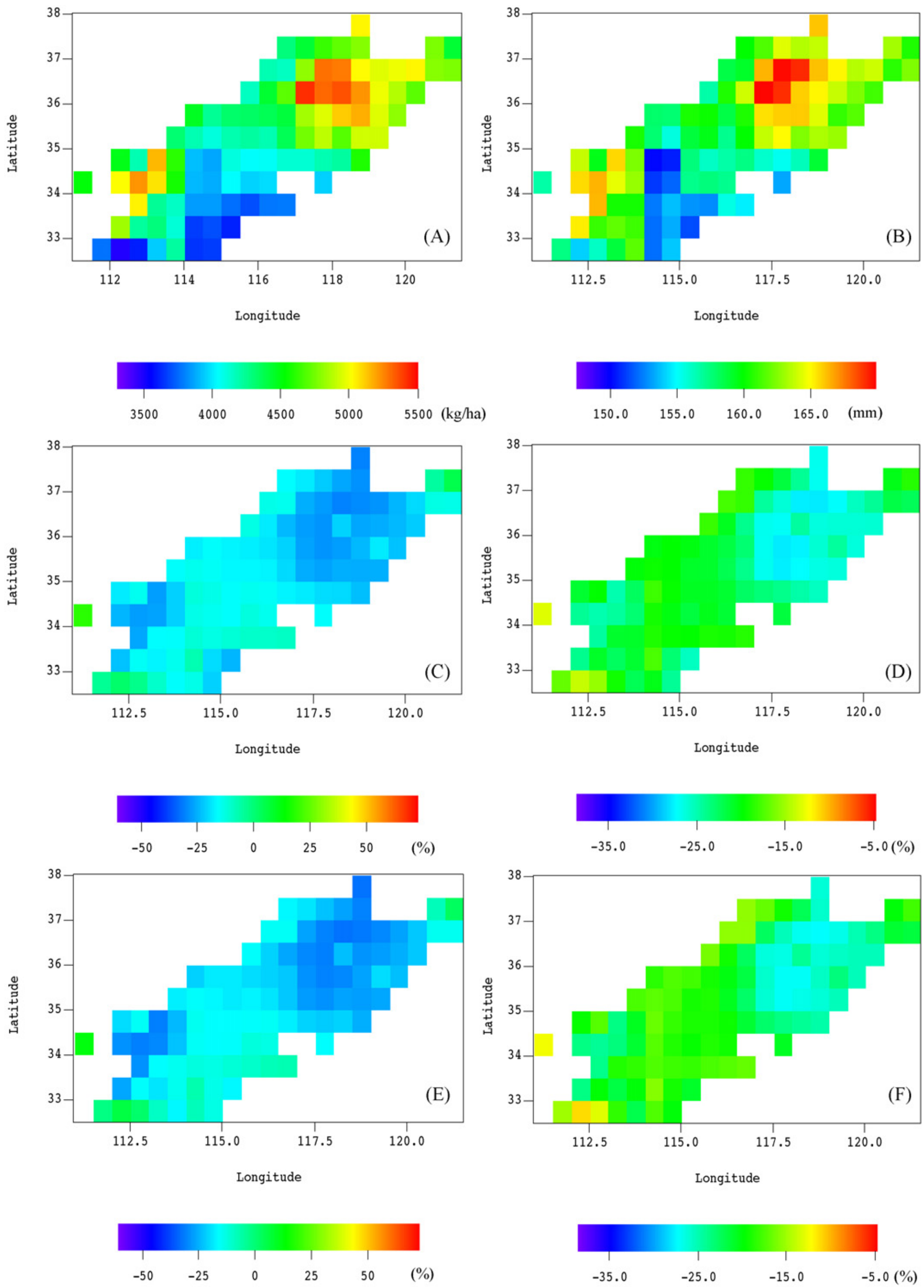

Fig. 6. Spatial patterns of simulated maize yield (A) and ET (B) during 1961–1990, and the projected changes in yield (C, E, G, I) and ET (D, F, H, J) during 2050s from the Experiments I (C, D), II (E, F), III (G, H), IV (I, J), respectively, using the crop variety II.

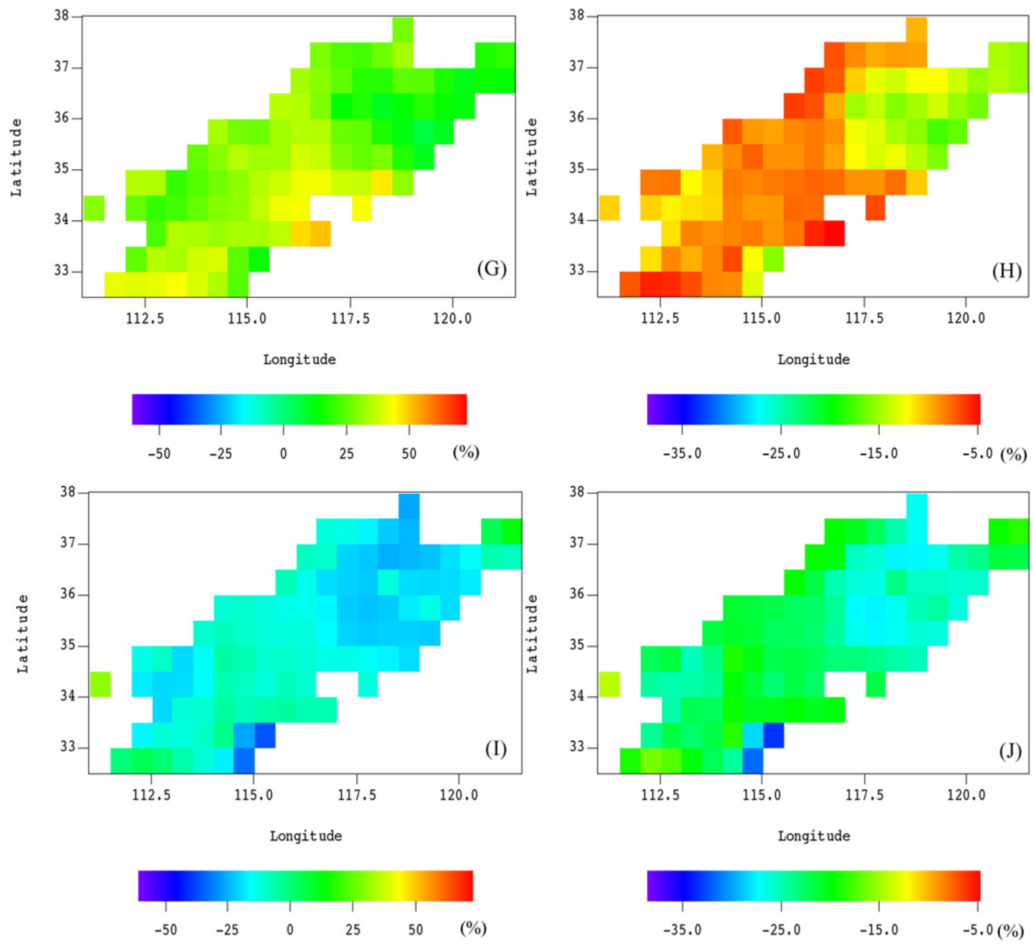

Fig. 6. (*Continued*.)

Such adaptation options can also be applicable in the NCP. For example, in Henan province, climate variability associated with East Asia summer monsoon and ENSO resulted in about 14.4 and 15.6%, respectively, of maize yield variability in the last several decades (Tao et al., 2004). Accordingly, maize cultivation areas in the province should be replaced by other crop in the years with El Niño phase or/and strong East Asia summer monsoon intensity.

4.2. Mechanisms of adaptation options and the uncertainties

The in-depth analyses in the grid of Zhengzhou and Jinan indicate that climate change could cause daily temperature to exceed *To* or even *Tm* at some days during maize growing period, consequently inhibit crop development and productivity. Shifting planting date based on variety properties could prevent the critical stages of crop development from coinciding with the extreme high-temperature period, consequently reducing yield loss from climate change to some extent. Developing new varieties that are high-temperature tolerant and have high thermal requirements may make full use of the improved heat resources due to climate change.

The estimated impacts and the contributions of the adaptation options can depend on the processes and mechanisms of a particular model used; particularly the approaches and performance of the model in simulating the physiological impacts of extreme weather events such as droughts and high-temperature stress. For example, Xiong et al. (2007), using CERES-Maize model and the A2 and B2 emission scenarios-based climate scenarios from a regional climate model, showed that rainfed maize yield in the North China Plain would increase by up to ≥50% during 2080s without adaptation, because of CO_2 fertilization effects. The CO_2 fertilization effects posed a 9–15% production increase compared to those without CO_2 effects in their study (Xiong et al., 2007). Some of previous studies simulated the impacts of high-temperature stress around flowering stage on crop yield by modifying crop harvest index (e.g., Horie et al., 1995; Challinor et al., 2005). Although the present version of the MCWLA does not explicitly simulate the high-temperature stress around flowering stage on crop yield, it does account for the impacts of extreme temperature stress on photosynthesis and subsequently on stomatal conductance, transpiration, and crop yield. Recent studies show that year-to-year variation in rice grain yield is attributed to nighttime temperature (Peng et al., 2004), which affects rice productivity through altered pollen germination and spikelet fertility (Mohammed and Tarpley, 2009). Since the mechanisms and the extent of the effects of high stress on crop development and productivity still remain uncertain, more controlled-environment and field observation experiments are needed to understand the processes and mechanisms of crop heat stress tolerance. In crop modelling studies, the robustness of crop models in capturing the impacts of weather extremes, intra-seasonal variability and climate thresholds is becoming increasingly important (e.g., Challinor et al., 2005; Porter and Semenov, 2005; Tao et al., 2009a).

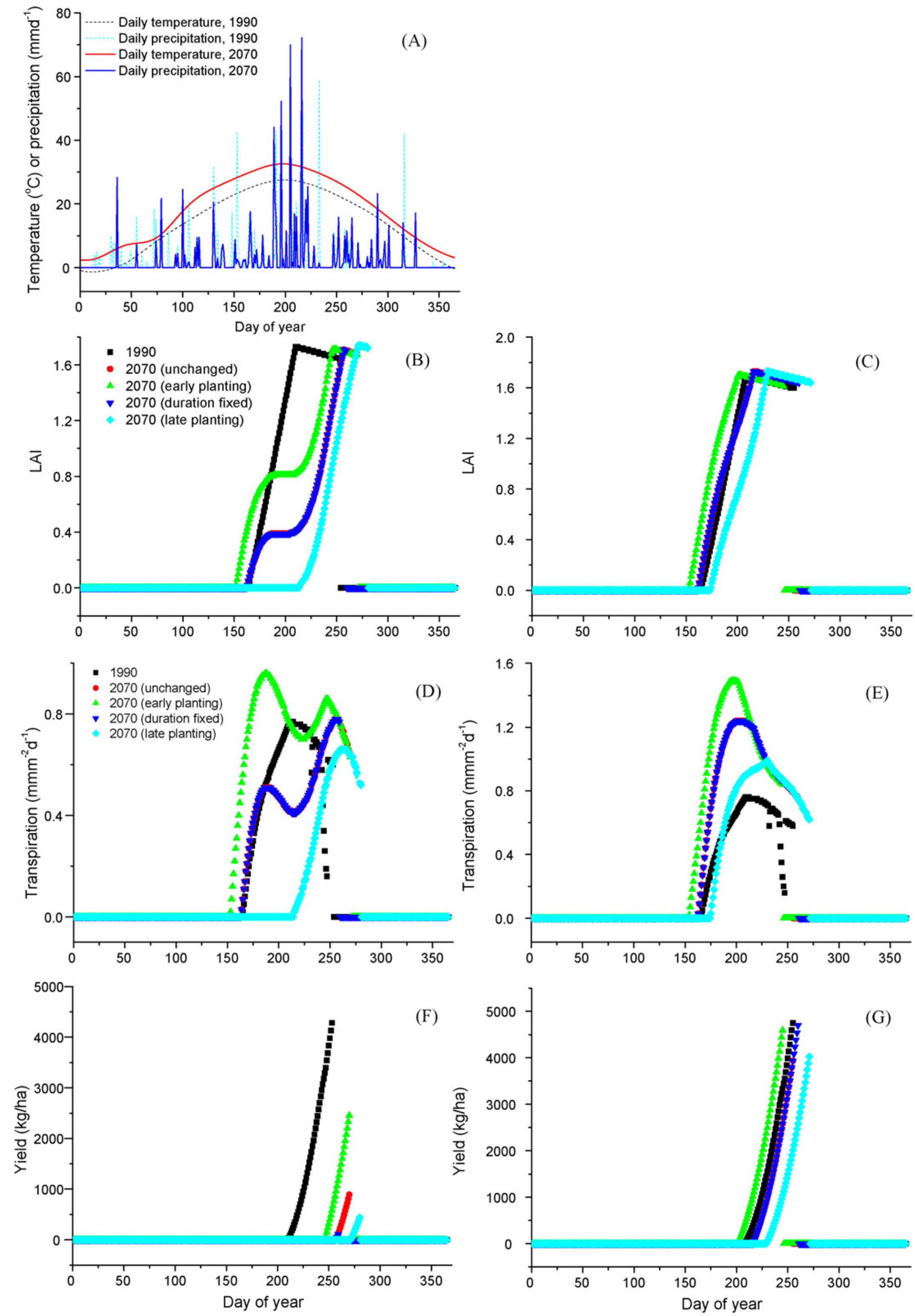

Fig. 7. Daily mean temperature and precipitation in 1990, and a climate scenario in 2070 based on HadCM3 GCM and A1FI emission scenario (A); and the simulated maize daily canopy LAI (B, C), transpiration (D, E) and yield (F, G) in 1990 and 2070 by Experiment I (unchanged), Experiment II (early planting), Experiment III (duration fixed), and Experiment IV (late planting), respectively, using the variety I (B, D, F) and variety II (C, E, G), at the grid of Zhengzhou.

Finally, to accurately understand impacts and develop effective adaptation strategies, adaptation should be seen as integrated part of the models used to simulate crop yields, farmers' income and other indicators related to agricultural performance. More integrated assessment taking the agricultural systems as a whole and taking as many available adaptation strategies as possible into account can be better informed of effective adaptation strategies.

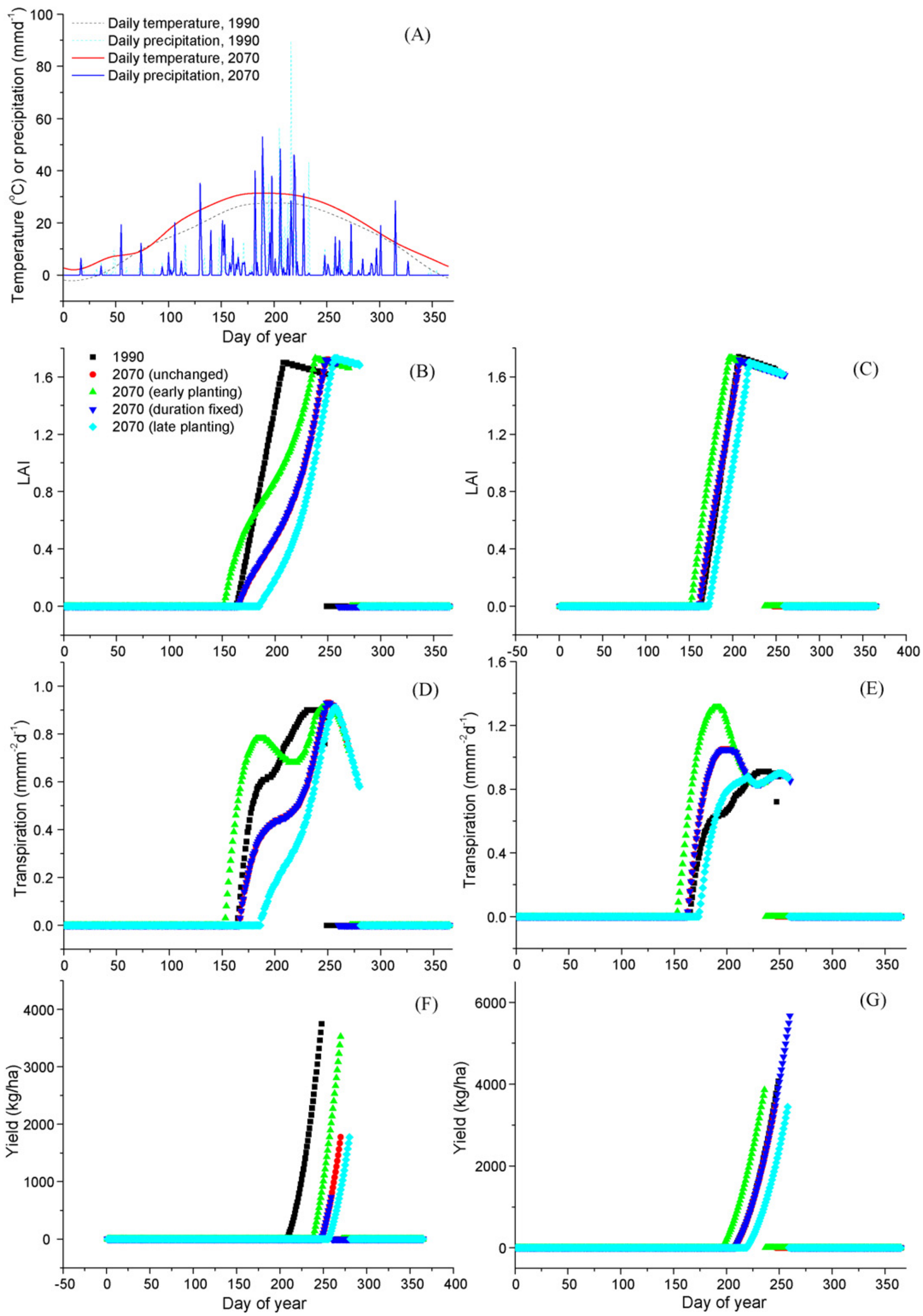

Fig. 8. Daily mean temperature and precipitation in 1990, and a climate scenario in 2070 based on HadCM3 GCM and A1FI emission scenario (A); and the simulated maize daily canopy LAI (B, C), transpiration (D, E) and yield (F, G) in 1990 and 2070 by Experiment I (unchanged), Experiment II (early planting), Experiment III (duration fixed), and Experiment IV (late planting), respectively, using the variety I (B, D, F) and variety II (C, E, G), at the grid of Jinan.

5. Conclusion

In this study, we take the general 'top-down' perspective to adaptation, that is, moving from GCMs to sector impact studies and then to quantify the relative contribution of adaptation options to maize production in the NCP.

We apply the super-ensemble-based probabilistic projection system to project maize productivity and water use during 2050s in the NCP, and to examine the relative contributions of adaptation options. Based on the large number of simulation outputs from the super-ensemble-based projection, we find that for the high-temperature sensitive varieties, early planting should be a generally effective adaptation option to reduce yield loss from climate change in the region; in contrast, for the high-temperature tolerant varieties, late planting could be a generally effective adaptation option. The spatial analysis shows that the relative contributions of adaptation options can be geographically quite different, suggesting the optimal adaptation strategies should be region and variety specific.

The biggest benefits will result from the development of new crop varieties that are high-temperature tolerant and have high thermal requirements, which can be a promising adaptation strategy, and worthy of large investments to avoid food crisis under global warming.

Acknowledgements

This study is supported by the 'Hundred Talents' Program of the Chinese Academy of Sciences, and National Key Programme for Developing Basic Science (Project Number 2009CB421105), China. We are grateful to the two anonymous reviewers and editor for their insightful comments on an earlier version of this manuscript.

References

Adger, W.N., Arnell, N.W., Tompkins, Emma, L., 2005. Successful adaptation to climate change across scales. Global Environ. Change 15, 77–86.
Challinor, A.J., Wheeler, T.R., Craufurd, P.Q., Slingo, J.M., 2005. Simulation of the impact of high temperature stress on annual crop yields. Agric. For. Meteorol. 135, 180–189.
Challinor, A., 2009. Towards the development of adaptation options using climate and crop yield forecasting at seasonal to multi-decadal timescales. Environ. Sci. Policy 12, 453–465.
Food Agriculture Organization of the United Nations (FAO), 1991. The Digitized Soil Map of the World (Release 1.0), vol. 67/1. FAO, Rome.
Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., Sitch, S., 2004. Terrestrial vegetation and water balance—hydrological evaluation of a dynamic global vegetation model. J. Hydrol. 286, 249–270.
Hannah, L.C., 2007. Seeds for the future. A review. Plant Sci. 173, 577–578.
Hansen, J.W., Challinor, A., Ines, A., Wheeler, T., Moron, V., 2006. Translating climate forecasts into agricultural terms: advances and challenges. Clim. Res. 33, 27–41.
Horie, T., Nakagawa, H., Centeno, H.G.S., Kropff, M.J., 1995. The rice crop simulation model SIMRIW and its testing. In: Matthews, R.B., Kropff, M.J., Bachelet, D. (Eds.), Modelling the Impact of Climate Change on Rice Production in Asia. CAB International, Oxon, UK, pp. 51–66.
IPCC, 2001. Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, UK, pp. 219–237.
IPCC, 2007. Climate change 2007: impacts, adaptation and vulnerability. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 273–313.
Jia, J.S., Liu, C.M., 2002. Groundwater dynamic drift and response to different exploitation in the North China Plain: a case study of Luancheng County Hebei Province. Acta Geograph. Sin. 57 (2), 201–209 (in Chinese).
Larcher, 1983. Physiological Plant Ecology. Springer, Heidelberg.
Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P., Naylor, R.L., 2008. Prioritizing climate change adaptation needs for food security in 2030. Science 319, 607–610.
McKeown, A., Warland, J., McDonald, M.R., 2005. Long-term marketable yields of horticultural crops in southern Ontario in relation to seasonal climate. Can. J. Plant Sci. 85, 431–438.
Meza, F.J., Wilks, D.S., 2003. Value of operational forecasts of seasonal average sea surface temperature anomalies for selected rain-fed agricultural locations of Chile. Agric. For. Meteorol. 116, 137–158.
Meza, F.J., Silva, D., Vigil, H., 2008. Climate change impacts on irrigated maize in Mediterranean climates: evaluation of double cropping as an emerging adaptation alternative. Agric. Syst. 98, 21–30.
Mitchell, T.D., Carter, T.R., Jones, P.D., Hulme, M., New, M., 2004. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100). Working Paper 55, Tyndall Centre for Climate Change Research, University of East Anglia, Norwich.
Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol. 25, 693–712.
Mo, X., Liu, S., Lin, Z., Guo, R., 2009. Regional crop yield, water consumption and water use efficiency and their responses to climate change in the North China Plain. Agric. Ecosyst. Environ. 134, 67–78.
Mohammed, A.R., Tarpley, L., 2009. High nighttime temperatures affect rice productivity through altered pollen germination and spikelet fertility. Agric. For. Meteorol. 149, 999–1008.
Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socioeconomic scenarios. Global Environ. Change 14, 53–67.
Peng, S., Huang, J., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X., Centeno, G.S., Khush, G.S., Cassman, K.G., 2004. Rice yields decline with higher night temperature from global warming. Proc. Natl. Acad. Sci. U.S.A. 101 (27), 9971–9975.
Porter, J.R., Semenov, M.A., 2005. Crop responses to climatic variation. Philos. Trans. R. Soc. B 360 (1463), 2021–2038.
Press, W.H., Teukolsky, S.A., Vetterling, W.T., Flannery, B.P., 1992. Numerical Recipes in FORTRAN: The Art of Scientific Computing, 2nd ed. Cambridge University Press, New York, pp. 107–110.
Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Rev. 100 (2), 81–92.
Reilly, J.M., Schimmelpfenning, D., 1999. Agricultural impact assessment, vulnerability, and the scope for adaptation. Clim. Change 43, 745–788.
Roberts, E.H., Summerfield, R.J., 1987. Measurement and prediction of flowering in annual crops. In: Atherton, J.G. (Ed.), Manipulation of Flowering. Butterworths, London, pp. 17–50.
Roderick, M.L., Farquhar, G.D., 2002. The cause of decreased pan evaporation over the last 50 years. Science 298, 1410–1411.
Reidsma, P., Ewert, F., Lansink, A.O., Leemans, R., 2010. Adaptation to climate change and climate variability in European agriculture: the importance of farm level responses. Eur. J. Agron. 32, 91–102.
Tao, F., Yokozawa, M., Hayashi, Y., Lin, E., 2003a. Changes in soil moisture in China over the last half-century and their effects on agricultural production. Agric. For. Meteorol. 118, 251–261.
Tao, F., Yokozawa, M., Hayashi, Y., Lin, E., 2003b. Future climate change, the agricultural water cycle, and agricultural production in China. Agric. Ecosyst. Environ. 95, 203–215.
Tao, F., Yokozawa, M., Zhang, Z., Hayashi, Y., Grassl, H., Fu, C., 2004. Variability in climatology and agricultural production variability in China in association with East Asian monsoon and El Niño Southern Oscillation. Clim. Res. 28, 23–30.
Tao, F., Hayashi, Y., Zhang, Z., Sakamoto, T., Yokozawa, M., 2008a. Global warming, rice production and water use in China: developing a probabilistic assessment. Agric. For. Meteorol. 148, 94–110.
Tao, F., Yokozawa, M., Liu, J., Zhang, Z., 2008b. Climate-crop yield relationships at province scale in China and the impacts of recent climate trend. Clim. Res. 38, 83–94.
Tao, F., Yokozawa, M., Zhang, Z., 2009a. Modelling the impacts of weather and climate variability on crop productivity over a large area: a new process-based model development, optimization, and uncertainties analysis. Agric. For. Meteorol. 149, 831–850.
Tao, F., Zhang, Z., Liu, J., Yokozawa, M., 2009b. Modelling the impacts of weather and climate variability on crop productivity over a large area: a new super-ensemble-based probabilistic projection. Agric. For. Meteorol. 149, 1266–1278.
Tubiello, F.N., Amthor, J.S., Boote, K.J., Donatelli, M., Easterling, W., Fischer, G., Gifford, R.M., Howden, M., Reilly, J., Rosenzweig, C., 2007. Crop response to elevated CO2 and world food supply: a comment on "Food for Thought" by Long et al., Science 312:1918–1921, 2006. Eur. J. Agron. 26, 215–223.
Wheeler, T.R., Craufurd, P.Q., Ellis, R.H., Porter, J.R., Vara Prasad, P.V., 2000. Temperature variability and the annual yield of crops. Agric. Ecosyst. Environ. 82, 159–167.
Xiong, W., Matthews, R., Holman, I., Lin, E., Xu, Y., 2007. Modelling China's potential maize production at regional scale under climate change. Clim. Change 85, 433–451.
Young, T.E., Ling, J., Geisler-Lee, C.J., Tanguay, R.L., Caldwell, C., Gallie, D.R., 2001. Developmental and Thermal Regulation of the Maize Heat Shock Protein HSP101. Plant Physiol. 127 (3), 777–791.
Zobler, L., 1986. A world soil file for global climate modelling. NASA Technical Memorandum 87802, 32.